# Thermodynamic analysis of three-cylinder steam turbine from combined cycle power plant

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***Abstract:*** *The paper present thermodynamic analysis of three-cylinder steam turbine, which operates in a combined cycle power plant. It is performed analysis of each turbine cylinder and of entire steam turbine. Comparison of steam turbine cylinders shows that intermediate pressure cylinder develops the highest real power and has the highest efficiencies while low pressure cylinder has the highest ideal (isentropic) power, the highest loses and the lowest efficiencies – therefore, improvement potential of the low pressure cylinder is the highest. Entire observed steam turbine has an energy efficiency equal to 86.58 % and exergy efficiency equal to 89.26 %, what is lower in comparison to high power steam turbines from some conventional land-based steam power plants but also higher in comparison to low power marine steam turbines.*

*KEYWORDS: STEAM TURBINE, COMBINED CYCLE POWER PLANT, THERMODYNAMIC ANALYSIS*

## *1. Introduction*

Combined cycle power plants are complex systems which consist of at least one gas turbine (Brayton process) and of at least one steam turbine (Rankine process) [1]. A connection between those two processes is heat recovery steam generator (HRSG) which uses exhaust heat from gas turbine(s) to produce steam for steam turbine [2]. HRSG must be carefully designed with an aim to utilize entire possible heat from exhaust gases and simultaneously to always produce steam of required operating parameters [3].

Literature review offers many analyses of combined cycle power plants. Exergo-economic and environmental analyses of solar integrated CCPP is presented [4]. Thermo-economic analysis of 300 MW CCPP can be found in the research of Oh et al. [5]. Liu and Karimi [6] proposed a new operating strategy for improving part-load performance of the analyzed combined cycle power plant. Riboldi and Nord [7] analyzed the integration of a wind farm into an offshore combined cycle power plant. In [8] can be found research about optimizing neural networks for combined cycle power plant electrical power output estimation.

In this paper is presented a thermodynamic analysis of three-cylinder steam turbine, which operates in a combined cycle power plant. It is performed calculation of efficiencies and loses for each cylinder and for the entire steam turbine. Obtained results show that by taking into account all the cylinders, low pressure cylinder has the lowest efficiencies (and the highest loses), therefore possible improvements should be based firstly on this cylinder.

## *2. Analyzed steam turbine description, characteristics and operating parameters*

General scheme of the analyzed steam turbine (along with operating points required for thermodynamic analysis) is presented in Fig. 1. Each cylinder is of single flow without steam extractions. All the cylinders are connected to the same shaft which drives an electric generator. It should be noted that in Fig. 1 are not presented all the components inside HRSG, presented are only elements through which passes main steam flow streams required for steam cylinders operation.

Steam operating parameters in each analyzed turbine operating point from Fig. 1 (steam mass flow rates, pressures and temperatures) are found in [5] and presented in Table 1. For each operating point, steam specific enthalpy, specific entropy and specific exergy are calculated from known steam pressure and temperature by using NIST-Refprop 9.0 software [9]. Specific exergies in each operating point from Table 1 and throughout this paper are calculated for the ambient pressure of 1 bar (100000 Pa) and the ambient temperature of 25 °C (298 K).

Real (polytropic) and ideal (isentropic) steam expansion processes inside each observed turbine cylinder in *h-s* diagram are presented in Fig. 2. Ideal process is characterized by always constant steam specific entropy during expansion, while in the real process steam specific entropy increases during expansion from each cylinder inlet to the outlet.

Comparison of ideal and real expansion processes inside each cylinder and for a whole steam turbine is the baseline for energy (isentropic) analysis, therefore in Table 2 are presented steam specific enthalpies for ideal (isentropic) expansion in each turbine cylinder. Operating points in Table 2 are marked in accordance with expansion processes presented in Fig. 2.

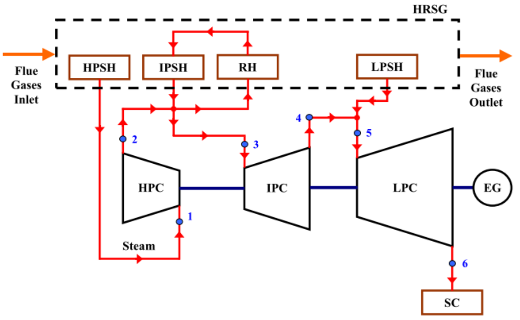

***Fig. 1.*** *Scheme of the analyzed steam turbine and operating points*

***Table 1.*** *Steam operating parameters in each operating point of the analyzed turbine*

| O.P.* | Pressure (bar) | Temperature (°C) | Mass flow rate (kg/s) | Specific enthalpy (kJ/kg) | Specific entropy (kJ/kg·K) | Specific exergy (kJ/kg) |
|---|---|---|---|---|---|---|
| **1** | 103.27 | 537.78 | 39.11 | 3467.90 | 6.7028 | 1474.00 |
| **2** | 17.58 | 300.25 | 39.11 | 3031.60 | 6.8380 | 997.40 |
| **3** | 16.87 | 518.51 | 54.78 | 3512.30 | 7.5676 | 1260.60 |
| **4** | 1.76 | 228.03 | 54.78 | 2928.00 | 7.6841 | 641.53 |
| **5** | 1.69 | 220.12 | 62.52 | 2912.40 | 7.6715 | 629.76 |
| **6** | 0.051 | 33.23 | 62.52 | 2440.30 | 7.9915 | 62.16 |

* Operating points refer to Fig. 1.

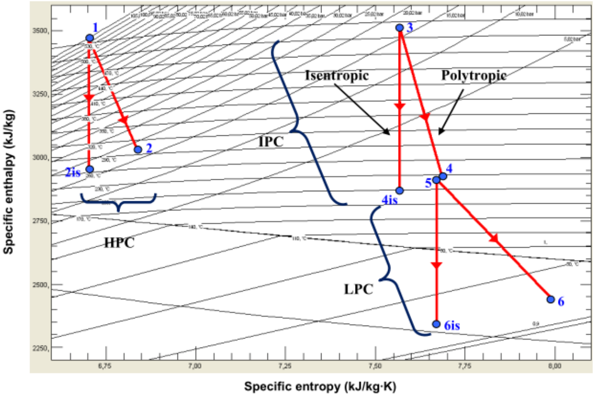

***Fig. 2.*** *h-s diagram of real (polytropic) and ideal (isentropic) expansion process in each turbine cylinder*

***Table 2.*** *Steam specific enthalpies for ideal (isentropic) expansion in each turbine cylinder*

| Operating | Pressure | Specific | Specific |
|---|---|---|---|

| **Point*** | **(bar)** | **enthalpy (kJ/kg)** | **entropy (kJ/kg·K)** |
|---|---|---|---|
| **1** | 103.27 | 3467.90 | 6.7028 |
| **2is** | 17.58 | 2956.30 | 6.7028 |
| **3** | 16.87 | 3512.30 | 7.5676 |
| **4is** | 1.76 | 2871.30 | 7.5676 |
| **5** | 1.69 | 2912.40 | 7.6715 |
| **6is** | 0.051 | 2342.20 | 7.6715 |

* Operating points refer to Fig. 2.

## *3. Equations for the energy and exergy analyses*

### *3.1. Energy and exergy analyses of any control volume*

Energy analysis of any control volume is defined by the first law of thermodynamics [10, 11]. Mass and energy balance equations for a control volume in steady state, while neglecting potential and kinetic energy, can be expressed according to [12, 13] by using equations:

$$\Sigma \dot{m}_{\text{in}} = \Sigma \dot{m}_{\text{out}} \,, \tag{1}$$

$$\dot{Q}_{\text{in}} + P_{\text{in}} + \Sigma(\dot{m} \cdot h)_{\text{in}} = \dot{Q}_{\text{out}} + P_{\text{out}} + \Sigma(\dot{m} \cdot h)_{\text{out}} \,. \tag{2}$$

The energy flow of any fluid stream can be calculated according to [14] as:

$$\dot{E}_{\text{en}} = \dot{m} \cdot h \,. \tag{3}$$

Exergy analysis of any control volume is defined by a second law of thermodynamics [15]. The exergy balance equation is defined, according to [16], as:

$$\Sigma(\dot{m} \cdot \varepsilon)_{\text{in}} + \dot{X}_{\text{heat}} = \Sigma(\dot{m} \cdot \varepsilon)_{\text{out}} + P + \dot{E}_{\text{ex,D}} \,, \tag{4}$$

where the exergy transfer by heat ( $\dot{X}_{\text{heat}}$ ) at the temperature $T$ can be defined according to [17] as:

$$\dot{X}_{\text{heat}} = \Sigma(1 - \frac{T_0}{T}) \cdot \dot{Q} \,. \tag{5}$$

Specific exergy of fluid stream is defined as [18]:

$$\varepsilon = (h - h_0) - T_0 \cdot (s - s_0) \,. \tag{6}$$

Similar to energy flow, the exergy flow of any fluid stream can be expressed as [19]:

$$\dot{E}_{\text{ex}} = \dot{m} \cdot \varepsilon = \dot{m} \cdot \left[ (h - h_0) - T_0 \cdot (s - s_0) \right] . \tag{7}$$

Energy and exergy efficiencies in general form can be defined as:

$$\eta_{\text{en (ex)}} = \frac{\text{energy (exergy) output}}{\text{energy (exergy) input}} \,. \tag{8}$$

These governing equations are used in observed steam turbine (and all of its cylinders) energy and exergy analysis.

### *3.2. Energy and exergy analyses of steam turbine from combined cycle power plant*

Energy (isentropic) analysis of observed steam turbine and all of its cylinders is based on comparison of real (polytropic) and ideal (isentropic) expansion processes [20, 21] according to operating points presented in Fig. 1 and Fig. 2 as well as according to steam operating parameters presented in Table 1 and Table 2. Exergy analysis of the observed steam turbine and its cylinders is based on real steam expansion processes only [22].

In Table 3 are summarized and presented equations for the energy analysis of each steam turbine cylinder, while in Table 4 are summarized and presented equations for the exergy analysis of each steam turbine cylinder. Equations for the energy and exergy analyses of the whole steam turbine are summarized and presented in Table 5.

***Table 3.*** *Equations for the energy analysis of observed steam turbine cylinders*

|  | **HPC** | **IPC** | **LPC** |
|---|---|---|---|
| Real (polytropic) power | $P_{\text{HPC,re}} = \dot{m}_1 \cdot (h_1 - h_2)$ | $P_{\text{IPC,re}} = \dot{m}_3 \cdot (h_3 - h_4)$ | $P_{\text{LPC,re}} = \dot{m}_5 \cdot (h_5 - h_6)$ |
| Ideal (isentropic) power | $P_{\text{HPC,is}} = \dot{m}_1 \cdot (h_1 - h_{2\text{is}})$ | $P_{\text{IPC,is}} = \dot{m}_3 \cdot (h_3 - h_{4\text{is}})$ | $P_{\text{LPC,is}} = \dot{m}_5 \cdot (h_5 - h_{6\text{is}})$ |
| Energy destruction | $\dot{E}_{\text{en,D,HPC}} = P_{\text{HPC,is}} - P_{\text{HPC,re}}$ | $\dot{E}_{\text{en,D,IPC}} = P_{\text{IPC,is}} - P_{\text{IPC,re}}$ | $\dot{E}_{\text{en,D,LPC}} = P_{\text{LPC,is}} - P_{\text{LPC,re}}$ |
| Energy efficiency | $\eta_{\text{en,HPC}} = \frac{P_{\text{HPC,re}}}{P_{\text{HPC,is}}}$ | $\eta_{\text{en,IPC}} = \frac{P_{\text{IPC,re}}}{P_{\text{IPC,is}}}$ | $\eta_{\text{en,LPC}} = \frac{P_{\text{LPC,re}}}{P_{\text{LPC,is}}}$ |

***Table 4.*** *Equations for the exergy analysis of observed steam turbine cylinders*

|  | **HPC** | **IPC** | **LPC** |
|---|---|---|---|
| Steam exergy flow-input | $\dot{E}_{\text{ex,HPC,S,in}} = \dot{m}_1 \cdot \varepsilon_1$ | $\dot{E}_{\text{ex,IPC,S,in}} = \dot{m}_3 \cdot \varepsilon_3$ | $\dot{E}_{\text{ex,LPC,S,in}} = \dot{m}_5 \cdot \varepsilon_5$ |
| Steam exergy flow-output | $\dot{E}_{\text{ex,HPC,S,out}} = \dot{m}_2 \cdot \varepsilon_2$ | $\dot{E}_{\text{ex,IPC,S,out}} = \dot{m}_4 \cdot \varepsilon_4$ | $\dot{E}_{\text{ex,LPC,S,out}} = \dot{m}_6 \cdot \varepsilon_6$ |
| Exergy destruction | $\dot{E}_{\text{ex,D,HPC}} = \dot{m}_1 \cdot \varepsilon_1 - \dot{m}_2 \cdot \varepsilon_2 - P_{\text{HPC,re}}$ | $\dot{E}_{\text{ex,D,IPC}} = \dot{m}_3 \cdot \varepsilon_3 - \dot{m}_4 \cdot \varepsilon_4 - P_{\text{IPC,re}}$ | $\dot{E}_{\text{ex,D,LPC}} = \dot{m}_5 \cdot \varepsilon_5 - \dot{m}_6 \cdot \varepsilon_6 - P_{\text{LPC,re}}$ |
| Exergy efficiency | $\eta_{\text{ex,HPC}} = \frac{P_{\text{HPC,re}}}{\dot{m}_1 \cdot (\varepsilon_1 - \varepsilon_2)}$ | $\eta_{\text{ex,IPC}} = \frac{P_{\text{IPC,re}}}{\dot{m}_3 \cdot (\varepsilon_3 - \varepsilon_4)}$ | $\eta_{\text{ex,LPC}} = \frac{P_{\text{LPC,re}}}{\dot{m}_5 \cdot (\varepsilon_5 - \varepsilon_6)}$ |

***Table 5.*** *Equations for the energy and exergy analyses of whole observed steam turbine*

| **Energy** | **WHOLE TURBINE** | **Exergy** | **WHOLE TURBINE** |
|---|---|---|---|
| Real (polytropic) power | $P_{\text{WT,re}} = \sum P_{\text{re,cylinders}}$ | Steam exergy flow-input | $\dot{E}_{\text{ex,WT,S,in}} = \sum \dot{E}_{\text{ex,S,in,cylinders}}$ |
| Ideal (isentropic) power | $P_{\text{WT,is}} = \sum P_{\text{is,cylinders}}$ | Steam exergy flow-output | $\dot{E}_{\text{ex,WT,S,out}} = \sum \dot{E}_{\text{ex,S,out,cylinders}}$ |
| Energy destruction | $\dot{E}_{\text{en,D,WT}} = P_{\text{WT,is}} - P_{\text{WT,re}}$ | Exergy destruction | $\dot{E}_{\text{ex,D,WT}} = \dot{E}_{\text{ex,WT,S,in}} - \dot{E}_{\text{ex,WT,S,out}} - P_{\text{WT,re}}$ |
| Energy efficiency | $\eta_{\text{en,WT}} = \frac{P_{\text{WT,re}}}{P_{\text{WT,is}}}$ | Exergy efficiency | $\eta_{\text{ex,WT}} = \frac{P_{\text{WT,re}}}{\dot{E}_{\text{ex,WT,S,in}} - \dot{E}_{\text{ex,WT,S,out}}}$ |

## *4. Results and discussion*

Real (polytropic) developed power of each cylinder and whole steam turbine, calculated according to data from Table 1, is presented in Fig. 3. In real exploitation, HPC develops the lowest real power equal to 17065.75 kW (when compared to other turbine cylinders). LPC develops real power of 29513.99 kW, while the highest real power is developed in IPC (32007.14 kW).

According to ideal (isentropic) steam expansion, Fig. 2, LPC will develop slightly higher power in comparison to IPC (35646.84 kW in comparison to 35113.09 kW), while the ideal power developed by HPC will remain the lowest (as real power) in comparison to the other cylinders.

Real (polytropic) developed power of the whole turbine is equal to 78586.88 kW, while in an ideal situation, when all steam expansion loses are neglected, analyzed turbine will develop ideal (isentropic) power equal to 90771.03 kW.

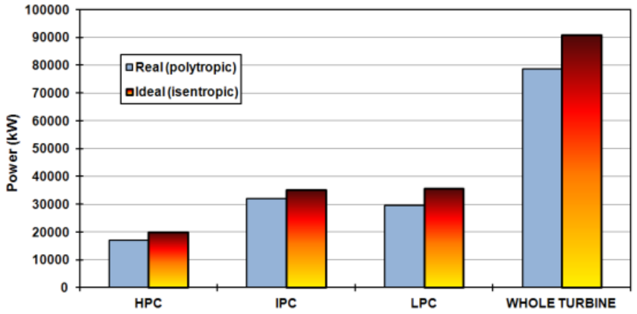

*Fig. 3. Real (polytropic) and ideal (isentropic) power of each turbine cylinder and the whole turbine*

Steam exergy flows at the input and output of each cylinder and the whole turbine are essential elements in the calculation of exergy destruction and efficiency. Steam exergy flows at the input and output of each turbine cylinder and the whole turbine are presented in Fig. 4.

From Fig. 4 can be seen that when comparing turbine cylinders, the highest steam exergy flow input (69053.92 kW) has IPC, while the highest steam exergy flow output (39013.02 kW) has HPC, what can be explained by a fact that steam after HPC will be used in two other cylinders, therefore high value of steam exergy flow at HPC output can be expected. The lowest steam exergy flow output, equal to 3886.08 kW has LPC, what is also expected because after LPC steam will be delivered to the condenser and will not be used anywhere in the steam turbine process. The high value of steam exergy flow at the LPC output (if occurs) will be indicator of increased losses (unused steam exergy) in the steam turbine process.

The whole observed turbine has a steam exergy flow at the input equal to 166079.34 kW, while steam exergy flow at the output of the whole turbine is 78041.23 kW.

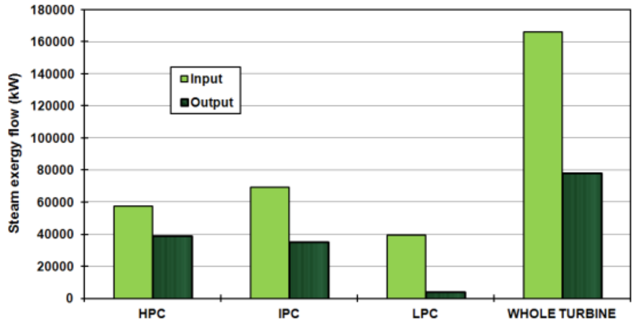

*Fig. 4. Steam exergy flows at the input and output of each turbine cylinder and the whole turbine*

Fig. 5 presents energy and exergy destructions (power loses) of each turbine cylinder and of entire analyzed steam turbine.

It can be clearly seen that energy destruction of each turbine cylinder and of entire steam turbine is higher in comparison with exergy destruction. If observing turbine cylinders, it can be concluded that both energy and exergy loses increases from the highest to the lowest steam pressure, therefore the lowest destructions (both energy and exergy) has HPC, followed by the IPC, while the highest destructions can be seen in LPC.

Whole observed steam turbine has energy destruction equal to 12184.14 kW, while exergy destruction of the whole turbine, according to presented steam operating parameters (Table 1), is 9451.23 kW.

For each turbine cylinder and for the whole observed steam turbine, exergy efficiencies are higher in comparison to energy efficiencies, Fig. 6.

In comparison to other cylinders, LPC has the lowest efficiencies (both energy and exergy), Fig. 6, due to the highest destructions, Fig. 5. Regardless of higher energy and exergy destructions, IPC has higher energy and exergy efficiencies in comparison to HPC.

The whole observed steam turbine has exergy efficiency equal to 89.26 %, while its energy efficiency is equal to 86.58 %. Calculated energy and exergy efficiencies of the whole turbine lead to conclusion that observed steam turbine has lower efficiencies in comparison to high power steam turbines from some conventional land-based steam power plants [23], but simultaneously higher in comparison to low power marine steam turbines [24, 25].

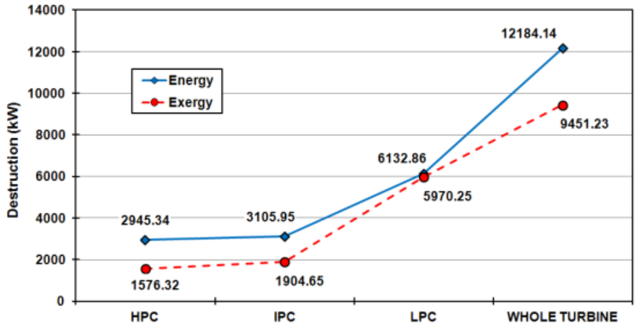

*Fig. 5. Energy and exergy destructions (power loses) of each turbine cylinder and the whole turbine*

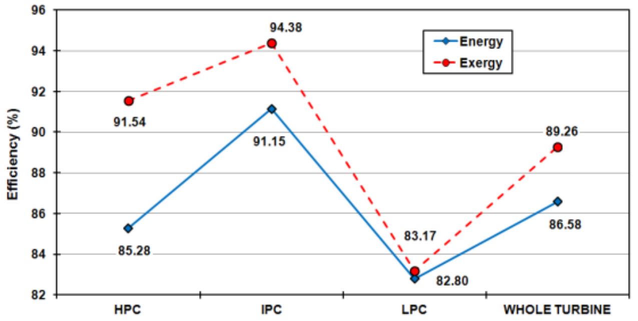

*Fig. 6. Energy and exergy efficiencies of each turbine cylinder and the whole turbine*

## 5. Conclusions

This paper presents a thermodynamic analysis of three-cylinder steam turbine, which operates in a combined cycle power plant. It is obtained developed power, energy and exergy efficiencies and loses for each steam turbine cylinder and for the entire steam turbine. The most important conclusions derived from this analysis are:

- When observing steam turbine cylinders, IPC develops the highest real power (32007.14 kW), while LPC has the highest ideal (isentropic) power of 35646.84 kW.
- For each cylinder and entire steam turbine it is observed that energy loses are higher and energy efficiencies are lower in comparison to exergy loses and exergy efficiencies.
- The highest loses and the lowest efficiencies (both energy and exergy) are observed in LPC what along with the highest ideal (isentropic) power show the highest improvement potential for this turbine cylinder (if compared to other cylinders).

Further research about this steam turbine will be based on its optimization and on finding possibilities for improving each cylinder operation, starting with a low pressure cylinder.

## 6. Acknowledgments

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**Nomenclature:**

| *Abbreviations:* | | *Greek symbols:* | |
|---|---|---|---|
| EG | Electric Generator | $\varepsilon$ | specific exergy, kJ/kg |
| HPC | High Pressure Cylinder | $\eta$ | efficiency, % |
| HPSH | High Pressure SuperHeater | | |
| HRSG | Heat Recovery Steam Generator | *Subscripts:* | |
| IPC | Intermediate Pressure Cylinder | 0 | ambient state |
| IPSH | Intermediate Pressure SuperHeater | D | destruction (loss) |
| LPC | Low Pressure Cylinder | en | energy |
| LPSH | Low Pressure SuperHeater | ex | exergy |
| RH | ReHeater | in | inlet (input) |
| SC | Steam Condenser | is | ideal (isentropic) |
| | | out | outlet (output) |
| *Latin symbols:* | | re | real (polytropic) |
| $\dot{E}$ | energy/exergy of a flow, kW | S | steam |
| $h$ | specific enthalpy, kJ/kg | WT | whole turbine |
| $\dot{m}$ | mass flow rate, kg/s | | |
| $p$ | pressure, Pa or bar | | |
| $P$ | power, kW | | |
| $\dot{Q}$ | heat transfer, kW | | |
| $s$ | specific entropy, kJ/kg·K | | |
| $T$ | temperature, K or °C | | |
| $\dot{X}_{\mathrm{heat}}$ | exergy transfer by heat, kW | | |

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